PAP-624

United States Department of the Interior
Bureau of Reclamation
Engineering and Research Center

Translation No.
Team No. General
Book No. 12,894

XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

HYDRAULICS BRANCH
OFFICIAL FILE COPY

PROTOTYPE MEASUREMENT AND ANALYSIS OF THE AERATION SLOTS IN THE WUJIANGDU AND FENGJIASHAN HYDRAULIC STRUCTURES

by

XIA Yu Chang

Tianjin Institute for Design and Survey
Ministry of Water Conservancy

Translated from the Chinese: Shuili Xuebao (Journal of Hydraulics,
No. 2, pp. 37-41, 1990

Translated by
Dr. David Hsu
Foreign Resources Associates

XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

Division of Foreign Activities
Code D-7200

USBR Translations
Denver, Colorado
January 1991

Team No. General
Book No. 12,894

PROTOTYPE MEASUREMENT AND ANALYSIS OF THE AERATION SLOTS IN THE WUJIANGDU AND FENGJIASHAN HYDRAULIC STRUCTURES

by

XIA Yu Chang

Abstract

Using dimensional analysis, the author discusses prototypic results of the aeration rate in cavitation prevention structures of the Wujiangdu and Fengjiashan spillways. The aeration ratio was found to be related to the flow energy ratio and the dimensions of the aeration slot. Correlation curves were plotted, using the measurements results obtained on the prototype, and an empirical equation was proposed for estimating the aeration ratio.

I. Practical Significance of Aeration Study

A number of hydraulics problems must be considered in building aeration and erosion-prevention structures for high-head spillways. One of the important issues is proper selection of the aeration pipe. The sectional area of the aeration pipe depends mainly on the aeration rate; without adequate aeration, cavitation erosion will not be effectively prevented. Conversely, excess aeration can lead to saturation of the flow, extension of the nappe and sidewall, and consequently an undesirable flow pattern. Aeration studies have been reported extensively in the literature. In this work an empirical equation for estimating the aeration rate of a channel/slot is proposed as a result of comprehensive analysis of prototypic measurement results of aeration slots in the Wujiangdu and Fengjiashan spillways.

II. Prototypic Observation of Aeration Rate in Aeration Slots of Wujiangdu and Fengjiashan Spillways

(1) Layout of Channel/Slot Combination Type of Aeration and Erosion-Prevention Structure

1. Left- and right-hand spillways at Wujiangdu. Elevation of the dam

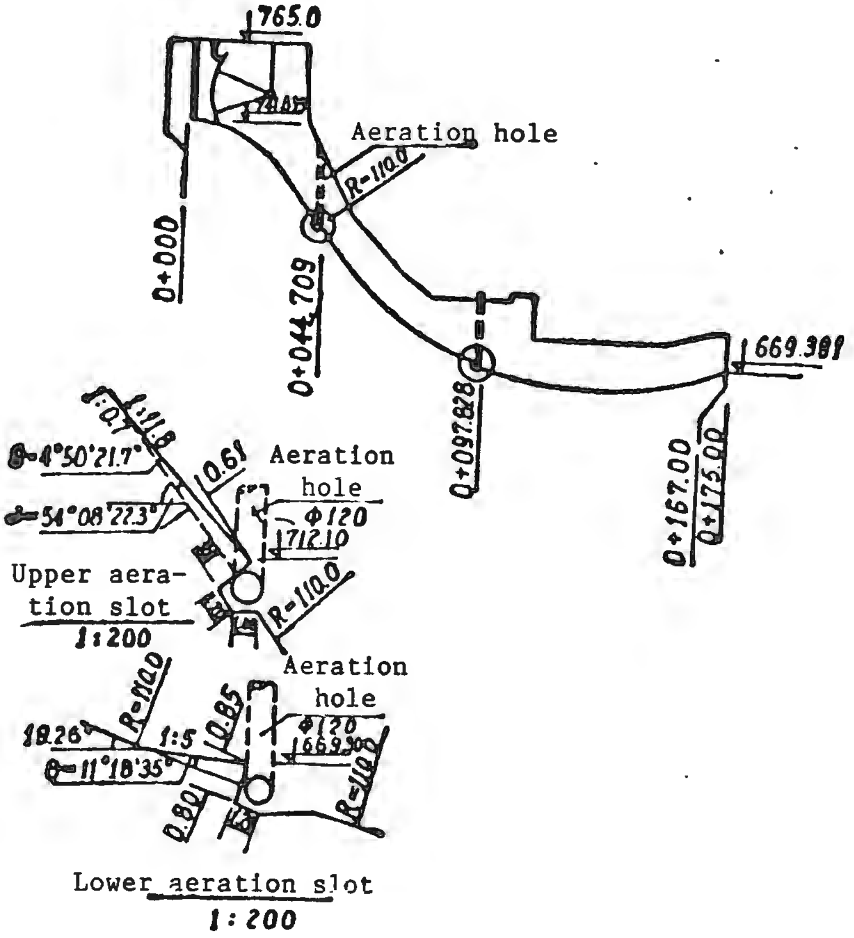


Figure 1 . Aeration slot layout in Wujiangdu spillway

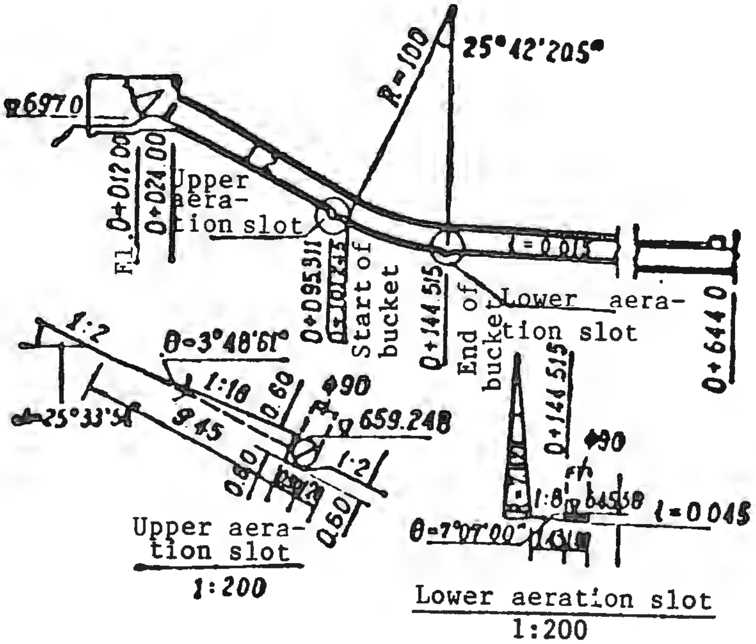


Figure 1 . Aeration slot layout in Fengjiashan Dam chute

is 741.619 m, the maximum head on the upstream face is 101 m, maximum single-width flow rate is 201 m^3/s-m, and the maximum flow velocity is 42 m/s. Two aeration channels were laid along the overflow surface of the spillway. The first channel is at the end (0+44.79) of the 1:0.7 slope reach of the overflow surface; the jump height is 0.61 m, slope is 1:11.8, channel width is 1.2 m, and channel depth is 0.93 m. Aeration pipes 1.2 m in diameter were installed in the two sidewalls of the right-hand ogee. For the left-hand ogee, only the left-hand sidewall has an operative aeration pipe 1.2 m in diameter; the pipe in the right-hand sidewall is clogged. The second aeration channel is installed in the mid reach (0+98.2) of the bucket reach. The jump height is 0.85 m, slope is 1:5, width is 1.2 m, and depth is 0.8 m. The two sidewalls each contain aeration pipes 1.2 m in diameter, as shown in Figure 1 .

Table 1. Working head and single-width flow rate of the aeration slot in the Wujiangdu spillway structure

Location of aeration channel	Head above the step Δz (m)	Single-width flow rate q (m^3/s-m)
Upper slot of left- and right-hand spillways	39.31-48.07	51.85-163.08
Lower slot of left- and right-hand spillways	82.44-90.8	51.85-163.08
Left-bank chute	77.64-86.61	38.9-236.11
No. 2 chute	71.1	52.15-164.64

2. Left-bank spillway at Wujiangdu. The elevation of the bottom inlet of the sluice is 720.0 m; the overflow surface is parabolic and unites with a 1:1.5 slope and the bucket reach. At the end of the slope reach (0+105.5), an aeration channel is installed. The step height is 0.38 m, slope is 1:17.5, width is 0.7 m, and depth is 1.4 m. Two aeration pipes 1.2 m in diameter are located in the two sidewalls. The outlets of one

pair of aeration pipes are located on the vertical wall downstream from the jump step.

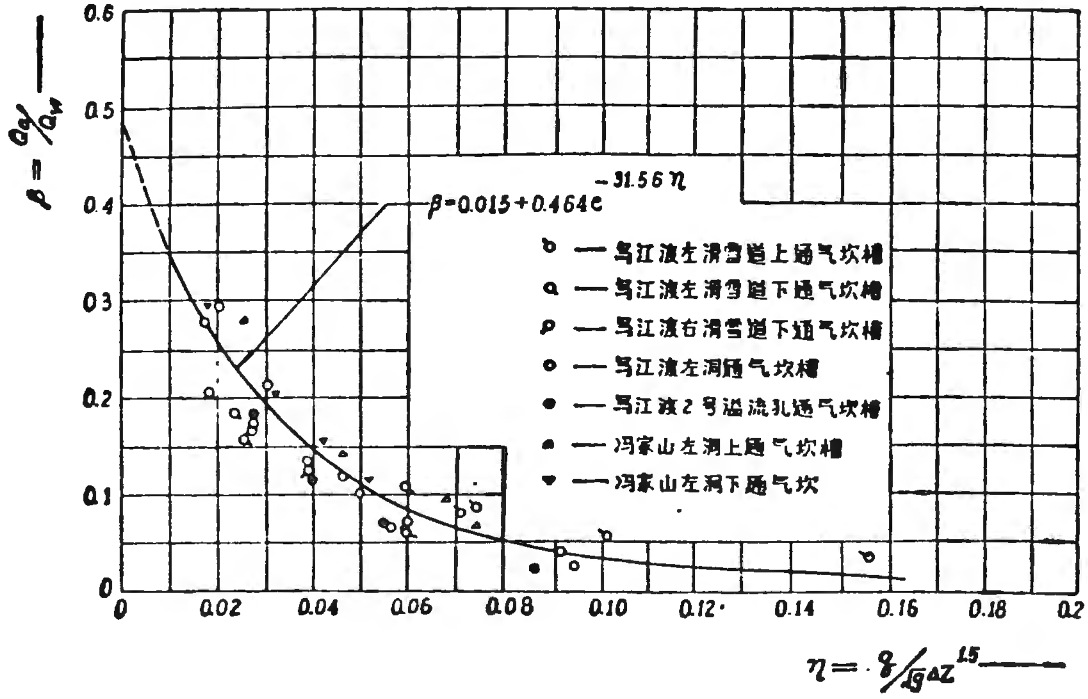
3. Overflow opening at Wujiangdu. Between the right- and left-hand ogees there are four overflow openings. Weir elevation is 742.0 m, and the overflow curve unites with a reach with 1:0.7 slope, followed by the bucket reach. At the end of the slope reach (0+59) an aeration channel is installed. Step height is 0.85 m, slope is 1:5, width is 1.34 m, and depth is 0.8 m. Aeration pipes 1.2 m in diameter are installed within the two sidewalls.

4. Fengjiashan left-bank chute. The inlet weir is at elevation 697.0 m; the overflow curve unites with a 1:2 slope, a bucket reach, and a horizontal reach. The total length is 922.23 m. An aeration channel is installed on the bucket reach and also near the lower tangent point. The upper aeration channel has a step height of 0.6 m, slope of 1:15, width of 0.9 m, and depth of 0.6 m. Aeration pipes 0.9 m in diameter are installed inside the two sidewalls. The lower aeration step has a height of 0.3 m, slope of 1:8, and the two sidewalls each contain an aeration pipe 0.9 m in diameter, as shown in Figure 1 .

(2) Prototype Measurement of Aeration

1. High flow speed prototype observation of the Wujiangdu Chute. The Wujiangdu Hydroelectric Powerplant operated its overflow in 1982 and 1983. High flow speed prototype observations were also made at the same time. The reservoir levels were 751.2 m and 760.2 m, respectively; both exceeded the design level of 750.0 m. The head on the aeration channel and the single width flow rate of the spillway structures are listed in Table 1.

The aeration measurements were made with a Pitot tube and a special



ɒ — Upper aeration slot of Wujiangdu left-bank spillway
ɑ — Lower aeration slot of Wujiangdu left-bank spillway
ρ — Lower aeration slot of Wujiangdu right-bank spillway
○ — Aeration channel of left-bank chute at Wujiangdu
● — Aeration channel of Wujiangdu No. 2 chute
▲ — Upper aeration slot of Fengjiashan left-bank chute
▼ — Lower aeration slot of Fengjiashan left-bank chute

Figure 2. Relationship between aeration ratio and flow engery ratio for an aeration slot

hot-sphere anemometer; the air speeds in the aeration pipe measured by these two instruments agreed well.

2. High flow speed prototype observation of the Fengjiashan left-bank chute. These observations were made in 1980 at a reservoir level of 707.01 to 706.82 m. The heads on the upper and lower aeration steps were 48 and 61 m, respectively, corresponding to gate openings of 2, 4, and 6 m and totally open. The single-width flow rates were 27.1, 47.5, 61.9 and 76.1 m^3/s-m, respectively.

III. Analysis of Prototype Aeration Measurement Data

When water flows over the aeration slot, the flow detaches from the jump and forms a water jet. The water jet is highly turbulent and hence mixes in air. In addition, a water-free cavity is formed below the jet. The pressure in the cavity is less than atmospheric. Due to this pressure difference, air is drawn into the aeration pipe. The ability of the water jet to mix in the air and the ability of the aeration pipe to supply air reach an equilibrium. The rate of aeration is therefore dependent upon the properties of the water, hydraulic parameters, and the dimensions of the aeration slot. Generally, this aeration can be described by the following equation:

$$q_e = f(v,\ h,\ \Delta z,\ \Delta p/\gamma,\ \rho,\ \mu,\ \sigma,\ g,\ \alpha,\ \theta,\ t,\ d). \qquad (1)$$

Using dimensional analysis, and following some simplification, a dimensionless expression is obtained:

$$\beta = f\left(\eta,\ Re,\ We,\ Ee,\ \alpha, \theta,\ \frac{t+d}{h}\right), \qquad (2)$$

where $\beta = Q_e/Q_w = q_e/q_s$, v, h, and Δz are flow velocity over the slot, depth, and head, respectively; ρ, μ, and σ are water density, viscosity coefficient, and surface tension, respectively; g is acceleration of gravity, $\Delta P/\gamma$ is empty chamber negative pressure (head); α is the bottom slope of the sidewall for the upstream flow of the aeration slot; θ, t, and d are the aeration slot slope, step height and slot depth, respectively; η, Re, Ee, and We are flow-energy ratio, Reynolds number, Euler number, and the Weber number, respectively.

In the prototype, viscosity and surface tension may be neglected. The flow is governed mainly by gravity. In geometrically similar situations the pressure field is determined by the velocity field; that is, dynamic similarity is automatically satisfied, and the Euler number is not taken

Table 2. Dimensions of slot and step of aeration and cavitation erosion reduction facility

Project name and location of aeration slot	Dimensions				Diameter of aeration slot, m
	Step height (m)	Step slope	Slot width (m)	Slot depth (m)	
Upper aeration slot of Wujiangdu left-bank spillway	0.61	1:11.8	1.2	0.93	2 x ϕ1.2
Lower aeration slot of Wujiangdu left-bank spillway	0.85	1:5	1.2	0.8	2 x ϕ1.2
Wujiangdu left-bank chute	0.38	1:17.5	0.7	1.4	4 x ϕ1.2
Wujiangdu chute No. 2	0.85	1:5	1.34	0.8	2 x ϕ1.2
Upper aeration slot of Fengjiashan left-bank chute	0.6	1:15	0.9	0.6	2 x ϕ0.9
Lower aeration step of Fengjiashan left-bank chute	0.3	1:8			2 x ϕ0.9

Note: Both sidewalls contain an aeration pipe. Only the right-hand side of the upper aeration slot in the left-bank spillway at Wujiangdu was plugged.

to be a variable. Hence, equation (2) can be simplified into the following expression:

$$\beta=f\left(\eta,\ \alpha,\ \theta,\ \frac{t+d}{h}\right). \qquad (3)$$

A total of 35 sets of aeration data were collected at seven aeration slots at the left- and right-hand spillways of Wujiangdu, at the left chute and the No. 2 overflow outlet of Wujiangdu, and at the left hole of Fengjiashan. A correlation curve is drawn on the basis of equation (3). Here the flow energy ratio is the primary variable, the aeration channel dimensions are the parametric variables, and the water-vapor ratio is the dependent variable. The results are shown in Figure 2.

Figure 2 shows that the 35 sets of prototype observation data are quite concentrated, and the effects of the aeration channel are not readily recognizable. The actually measured results show that, within the above range of aeration channel dimensions, the water-vapor ratio is related mainly to the flow energy and not affected by the aeration channel dimensions to any noticeable extent. Curve fitting yielded the following empirical expression:

$$\beta=0.015+0.464e^{-31.66\eta} \tag{4}$$

The above equation is valid when the flow energy ratio($\eta=q/\sqrt{q}\,\Delta z^{1.5}$) falls between 0.018 and 0.156. The dimensions of the aeration channel are listed in Table 2 below.

In addition, three correlation graphs were plotted, including $\beta = f(Q_U$, channel dimensions), $\beta = f(Fr$, channel dimensions), and $\beta = f(\eta$, channel dimensions). A comparison shows that the correlation is best among the $\beta = f(\eta$, channel dimensions) group.

REFERENCES

1. Research Report on the Prototype Observation of Aeration and Erosion Reduction for the Fengjiashan Reservoir Chute. Prototype Observation Group at the Fengjiashan Reservoir Chute, November, 1981.
2. Final Report on the High Speed Water Flow Prototype Observation of Wujiangdu Hydroelectric Powerplant. South Central Institute of Survey and Design. Ministry of Water Conservancy and Electric Power, July, 1983.
3. XIA Yu Chang, WANG Shan Da, WEI You Zhong. Research Report on Aeration and Erosion Reduction Facilities. Tianjin Institute of Survey and Design, and South Central Institute of Survey and Design, Ministry of Water Conservancy and Electric Power, January 1984.

Received by Editors 20 October, 1988

水 利 学 报

1990年 第2期 (月刊)*

目 录

短文

科技动态

---

* 出版日期：1990年 2 月28日.总期号：第157期。

利

本文首先对
流运移的TFM
了盐分通过0—
有关描述土壤
水分在土壤孔
讨论；最后指

溶质（盐
的支配，同时
测手段的改善，
确定性数学模
如盐分的溶解
可动水体中不
可以得到溶质
分运移过程所
中运移过程的
件外，一般难
运移过程作出
关心的是盐
随机过程处
等[4-7]的盐
较简单和便
设所研
土体内的运

---

* 本文
收到。

偏差比	样本ET_0的标准偏差
⑧	⑨
.9664	0.2118
.8723	0.3456
.8735	0.429
.8675	0.4618
.9666	0.4226
.9717	0.3582
.8779	0.2118
.7672	0.3456
.7540	0.429
.7009	0.4618
.7534	0.4226
.8539	0.3582

45°方向（东北
方向上的半变异
内十分接近，故
90°两个方向上
$ET_0(x)$受

$ET_0(x)$之间，
随之消失．出现
度等）在区域上

成反比关系．至
（或协方差函

数）的优点，正是在于它能综合地反映空间结构信息，并能给予量化．因而，它是分析空间变异性的重要工具．

（三）半变异函数在原点附近的性状　根据定义，在原点处$\gamma(h)=0$，但在实际应用中，如ET_0及其它一些物理量的半变异函数[2, 8]，在原点处$\gamma(h)\neq 0$，即出现间断．地质统计学称此现象为“块金效应”（Nugget effect），它属于白噪声（White noise）一类的随机现象．本文中ET_0半变异函数的“块金效应”均很小，$C_0=0.005$—0.008，它对于分析ET_0的空间变异几乎不起作用．但是，对于局部气流扰动频繁或受干热风影响较大的地区，ET_0以及实际作物需水量均可能出现较大的“块金效应”，需要作具体研究．

致谢　湖北、湖南两省作物需水量等值线图研制组茆智、李生璿、李远华、吴化南、余健来、刘振林等为本文提供了参照作物需水量数据．

参考文献

［1］ Journel, A.G.等著，矿业地质统计学．侯景儒等译，冶金工业出版社，1982年．

［2］ Spatial variability, Special Issue of Agri. *Water Management*, Vol.6, 1983, Netherlands.

［3］ 湖北省水利厅、武汉水利电力学院，湖北省参考作物需水量及水稻需水量等值线图研究．1986年．

［4］ 茆智、李远华，作物需水量等值线图的原理、绘制与应用、水利学报，1988年第1期．

［5］ 袁新，空间变异理论及在需水量研究中的应用．武汉水利电力学院硕士研究生论文，1988年．

［6］ 李恩羊，空间变异理论及应用．武汉水利电力学院，1988年．

［7］ 王仁铎、胡光道，线性地质统计学．地质出版社，1988年．

［8］ Delhomme, J.P., Kriging in the hydrosciences. *Advances in Water Resources*, Vol.1, No.5, 1978.

乌江渡、冯家山泄水建筑物通气坎槽通气量原型观测成果分析*

夏 毓 常

（水利部天津勘测设计院）

提　要

本文以尺度分析法为基础，对乌江渡、冯家山两工程通气减蚀设施通气量原型观测成果进行分析研究，查明通气比系与流能比及通气坎槽尺寸有关．由原型观测资料绘出相关曲线，并提出估算通气比的经验公式．

---

* 本文于1988年10月20日收到．

一、通气量研究的实际意义

高水头泄水建筑物设置通气减蚀设施时，所需研究的水力学问题很多，其中如何正确地选择通气管，就是一项重要的内容．而通气管面积主要取决于通气量．若通气量不足，则减免空蚀效果差．反之，若通气量过多，使得水流含气饱和，并因水翅的扩展而引起边墙的加高，进而造成不良流态．关于通气量研究，前人已有不少研究成果，本文根据乌江渡、冯家山泄水建筑物通气坎槽通气量原型观测成果，经综合分析，提出估算坎槽组合式通气量的经验公式．

二、乌江渡、冯家山泄水建筑物通气坎槽通气量原型观测

（一）坎槽组合式通气减蚀设施布置

1．*乌江渡左、右滑雪道*　滑雪道堰顶高程为741.619m，反弧段最高水头为101m，最大单宽流量为201m³/s·m，最大流速为42m/s．沿滑雪道溢流面布置两道通气坎槽：在溢流面1:0.7斜坡段末端处（0＋44.79）布置第一道，挑坎高度0.61m，坎坡1:11.8，槽宽1.2m，槽深为0.93m，右滑雪道两侧边墙内各设直径为1.2m的通气管，而左滑雪道仅左侧边墙内1.2m直径的通气管起作用，右侧通气管阻塞不通．第二道通气坎槽设在反弧段的中部（0＋98.2），挑坎高度0.85m，坎坡为1:5，槽宽1.2m，槽深0.8m，两侧边墙内各设置直径为1.2m的通气管．其布置参见图1*a*．

2．*乌江渡左岸泄洪洞*　泄洪洞进口底部高程为720.0m，溢流面呈抛物线，下接1:1.5斜坡段与反弧段．在斜坡段末端处（0＋105.5）设置一道通气坎槽，挑坎坎高0.38m、坎坡1:17.5，槽宽0.7m，槽深1.4m，两侧边墙内各设置直径为1.2m的两个通气管，其中一对通气管的出口设在挑坎下游垂直壁面上．

3．*乌江渡溢流孔*　在左、右滑雪道之间，设置4孔溢流孔．溢流孔的堰顶高程742.0m，溢流曲线段下接1:0.7斜坡段，再接反弧段．在斜坡段末端处（0＋59），设置一道通气坎槽，坎高0.85m，坎坡1:5，槽宽1.34m，槽深为0.8m，两侧边墙内各设直径为1.2m通气管．

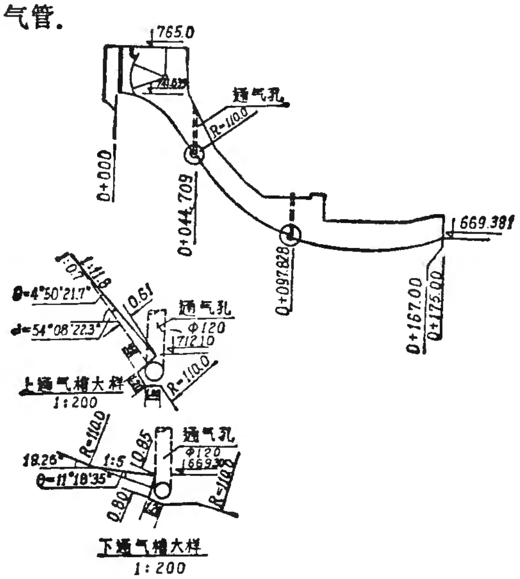


图 1*a*　乌江渡滑雪道通气槽布置

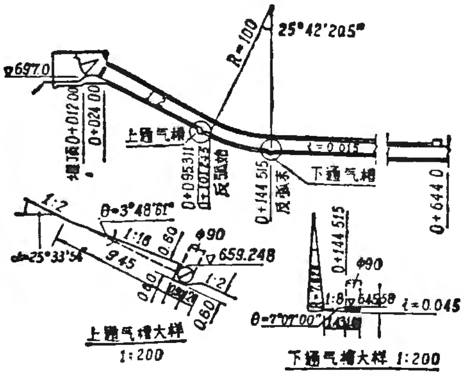


图 1*b*　冯家山水库溢洪洞通气槽布置

4.冯家

反弧段、及

坎槽．上通

为0.9m的通

其布置参见

（二）

1.乌江

泄洪运用，

超过设计水

通

左、

左、

左岸

2号

通气

测量结果

2.冯

位为707.

为2、4、

当水

气．另外

管供给．

流性质、

由

式中：

分别为

*α*为通

Re、*Ee*

在

似情况

量．综

4.冯家山左岸溢洪洞　溢洪洞进口堰顶高程697.0m，溢流曲线段下接1:2斜坡段、反弧段、及水平段．全长共922.23m．在反弧段上、下切点附近处分别各设置一道通气坎槽．上通气坎坎高0.6m，坎坡1:15，槽宽0.9m，槽深 0.6m，两侧边墙内各 设直径为0.9m的通气管．下通气坎坎高0.3m，坎坡1.8，两侧边墙内各设直径为0.9m通气管，其布置参见图1b．

（二）通气量原型观测工况

1.乌江渡泄水建筑物高速水流原型观测　乌江渡水电站于1982年及1983年先后两次泄洪运用，同时进行了高速水流原型观测．其库水位分别为751.2m及760.2m左右，均已超过设计水位(750.0m)．各泄水建筑物通气坎槽上的水头及单宽流量如表1所列．

表 1　乌江渡泄水建筑物通气坎槽工作水头及单宽流量

通气坎槽部位	坎上水头 Δz(m)	单宽流量 q(m³/s·m)
左、右滑雪道第一道	39.31—48.07	51.85—163.68
左、右滑雪道第二道	82.44—90.8	51.85—163.68
左岸泄洪洞	77.64—86.61	38.9—236.11
2号溢流孔	71.1	52.15—164.64

通气量观测，系同时采用毕托管及特制热球风速仪两种仪器测量通气管风速，二者测量结果甚为接近．

2.冯家山左岸溢洪洞高速水流原型观测　1980年曾进行了高速水流原型观测，库水位为707．01—706.82m，上、下通气坎坎上水头分别为 48m及 61m，相应于闸门开度为2、4、6m及全开情况下，单宽流量分别为27.1，47.5，61.9及76.1m³/s·m．

三、通气量原型观测成果分析

当水流越过通气坎槽，水流脱离挑坎而形成挑流水舌，由于水舌高度紊动而掺入空气．另外，在水舌下方形成无水空腔，空腔内压力低于大气压力，空气籍压力差由通气管供给．水舌掺气能力与通气管供气能力应保持平衡状态．因此，通气管通气量系与水流性质、水力要素和通气坎槽尺寸等因素有关，一般可用下式表示：

$$q_a=f(v,\ h,\ \Delta z,\ \Delta p/\gamma,\ \rho,\ \mu,\ \sigma,\ g,\ \alpha,\ \theta,\ t,\ d). \tag{1}$$

由尺度分析，经整理后，可得无量纲表达式：

$$\beta=f\left(\eta,\ Re,\ We,\ Ee,\ \alpha,\theta,\ \frac{t+d}{h}\right), \tag{2}$$

式中：$\beta=Q_a/Q_w=q_a/q_w$气水比；v、h、Δz分别为坎上流速，水深、及水头；ρ、μ、σ分别为水的密度、粘滞系数、及表面张力；g为重力加速度；$\Delta P/\gamma$为空腔负压(水头)；α为通气坎槽上游来流边壁底坡；θ、t、d分别为通气坎槽坡度、坎高及槽深；η、Re、Ee、We分别为流能比、雷诺数、欧拉数及韦伯数．

在原型中，粘滞力及表面张力影响均可不计．水流运动主要由重力控制，在几何相似情况下，压力场系由流速场决定，亦即自动满足动力相似，因而欧拉数也可不作为变量．综上所述，则可将式(2)简化为下式：

$$\beta=f\left(\eta,\ \alpha,\ \theta,\ \frac{t+d}{h}\right). \tag{3}$$

由乌江渡左、右滑雪道，乌江渡左洞、乌江渡 2 号溢流孔，及冯家山左洞等七处通气坎槽的35组通气量原型观测资料，按式(3)作出相关曲线图，其中以流能比作为主变量，通气坎槽尺寸作为参变量．水气比作为应变量，如图 2 所示。

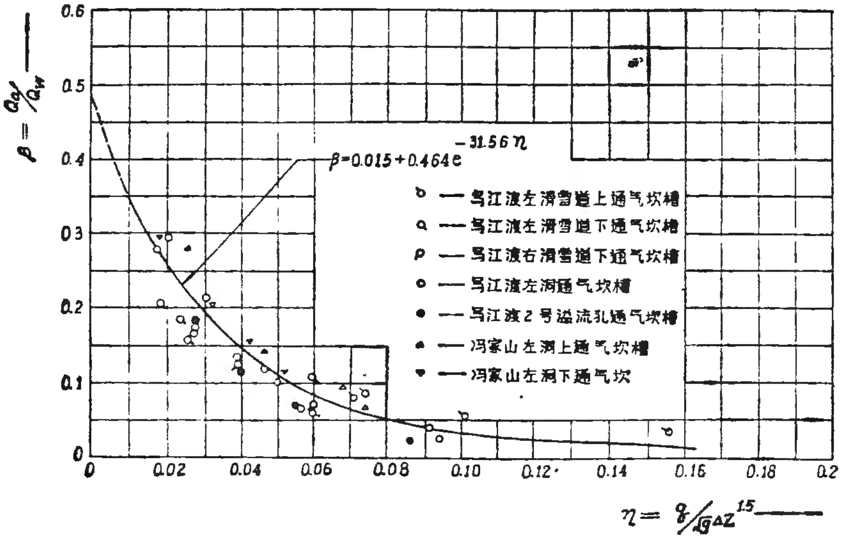


图 2　通气坎槽通气比与流能比关系

从图 2 看出，35组原型观测点据比较集中，不易分辨出通气坎槽的影响趋势和程度．实测资料说明，在上述通气坎槽尺寸变化范围内，气水比主要与流能比有关，而与通气坎槽尺寸相关不明显．通过曲线拟合，可用下列经验公式表示．

$$\beta=0.015+0.464e^{-31.56\eta}. \tag{4}$$

上式应用范围：流能比（$\eta=q/\sqrt{q}\,\Delta z^{1.5}$）在0.018到0.156之间，通气坎槽组合式尺寸范围如表 2 所列．

表 2　通气减蚀设施坎槽组合式尺寸

工程名称及通气坎槽部位	通气坎槽尺寸				通气管直径
	坎高 (m)	坎坡	槽宽 (m)	槽深 (m)	(m)
乌江渡滑雪道上通气坎槽	0.61	1:11.8	1.2	0.93	2×φ1.2
乌江渡滑雪道下通气坎槽	0.85	1:5	1.2	0.8	2×φ1.2
乌江渡左泄洪洞	0.38	1:17.5	0.7	1.4	4×φ1.2
乌江渡 2 号溢流孔	0.85	1:5	1.34	0.8	2×φ1.2
冯家山左洞上通气坎槽	0.6	1:15	0.9	0.6	2×φ0.9
冯家山左洞下通气坎	0.3	1:8			2×φ0.9

注　通气管两侧边墙内均有，仅乌江渡左滑上通气坎槽右侧堵塞。

此外，在资料分析过程中，曾分别作过 $\beta=f(q_w$、坎槽尺寸)、$\beta=f(Fr$、坎槽尺寸)，及$\beta=f(\eta$，坎槽尺寸)三种相关曲线图，比较结果表明，以其中 $\beta=f(\eta$、坎槽尺寸）相关关系最好．

参考文献

[1] 冯家山水库溢洪洞通气减蚀原型观测研究报告．冯家山水库溢洪洞原型观测组，1981年11月．

[2] 乌江渡水电站高速水流原型观测成果总报告．水利电力部中南勘测设计院，1983年7月．

[3] 夏毓常、王善达、韦有忠，通气减蚀设施通气量研究报告．水利电力部天津勘测设计院、水利电力部中南勘测设计院，1984年1月．

测压管系统传递函数及其在滑坡涌浪波压测量中的应用*

黄荣彬

（能源部　西北勘测设计院科研所）

提　要

本文把测压管系统作为线性系统，建立振动系统的数学模型，经拉普拉斯变换，导出了系统的传递函数和频率特性以及测压管最大读数与墙面测点最大净波压强的关系式．这样，可以从测压管的最大读数计算出净波压强的最大值．

一、测压系统的微分方程

（一）基本假定

1．涌浪压力作用在垂直墙面上；

2．测压系统是一个线性系统；

3．系统中的非恒定流水头损失可按恒定流相应流速下的沿程水头损失来近似地代替．

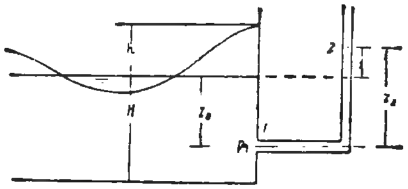


图 1　测压系统

（二）系统的微分方程

设测压系统如图 1 所示．当发生涌浪时，直墙上1\#点的压强为 p_1．测压管水面将从静水面上升到2\#点．可列1—1和2—2的能量方程如下：

$$z_1+\frac{p_1}{\gamma}+\frac{v_1^2}{2g}=z_2+\frac{p_2}{\gamma}+\frac{v_2^2}{2g}+\sum h_w+\frac{l}{g}\frac{dv}{dt}, \qquad (1)$$

其中：l——自点 1 至静水面的水柱长度；Σh_w——包括局部和沿程的总水头损失；$\frac{p_1}{\gamma}=\frac{p_0}{\gamma}+z_0+p(t)$；$z_1=0$；$v_1=v_2$；$p_2=p_0$；$z_2=z_0+z$；$p_0$——大气压力．

于是式（1）可写成：

$$z+\Sigma h_w+\frac{l}{g}\frac{dv}{dt}=p(t). \qquad (2)$$

设测压管内径为 d，根据第 3 点假定、并考虑管内为层流（在模型试验中，实测管

---

* 本文于1988年12月7日收到．